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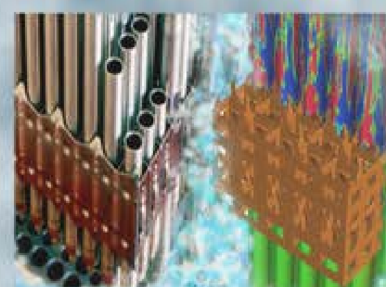
AP1000® PWR Startup Core Modeling and Simulation with VERA-CS



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AP1000® PWR STARTUP CORE MODELING AND SIMULATION WITH VERA-CS

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ABSTRACT

This paper describes the application of the Core Simulator of the Virtual Environment for Reactor Applications, VERA-CS, under development by the Consortium for Advanced Simulation of LWRs (CASL) to the core physics analysis of the AP1000® PWR. The AP1000 PWR features an advanced first core with radial and axial heterogeneities and at-power control rods insertion to perform the MSHIM™ advanced operational strategy. These advanced features make application of VERA-CS to the AP1000 PWR first core especially relevant to qualify VERA performance. This paper focuses on the qualification efforts at hot zero power conditions, where Monte-Carlo reference solutions have been established. The comparison of both global core parameters (e.g. critical boron concentration, rod worth and reactivity coefficients) and fine-mesh fission rate spatial distribution indicate excellent numerical agreement between VERA-CS and the Monte-Carlo predictions across the simulations performed.

Key Words: AP1000 PWR, MSHIM, VERA, KENO

1 INTRODUCTION

This paper describes the application of the Virtual Environment for Reactor Applications, Core Simulator, VERA-CS, under development by the Consortium for Advanced Simulation of LWRs (CASL), to the core physics analysis of the AP1000 PWR. The AP1000 PWR has a low-leakage 18-month cycle advanced first core [1] featuring five fuel regions with intra-assembly enrichment zoning and a combination of burnable absorbers: the Westinghouse Integral Fuel Burnable Absorber (IFBA) a ZrB_2 coating on the pellet surface, and the Wet Annular Burnable Absorber (WABA), an insert employed at selected guide thimble locations. The core loading pattern is depicted in Figure 1. Figure 1 also shows the assembly loading pattern for Region D fuel, featuring radial enrichment zoning (3 enrichments), 68 IFBA rods, 8 “long” and 4 “short” WABA inserts. The long and short WABA inserts

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differ in the axial length (longer or shorter) of the poisoned-bearing region, with the top plena and lower Zr spacer varying accordingly. Region E fuel assemblies are similarly characterized by enrichment zoning, IFBA rods and, when present, axially heterogeneous WABA inserts. Lower-enriched axial blankets are employed for Regions C, D and E; the blankets for the IFBA rods consist of annular fuel with a central void to accommodate He release from ^{10}B neutron absorptions in ZrB_2. For the various fuel regions, Table 1 provides the average enrichment at the core mid-plane, the number of assemblies in the core (out of 157 total) pertaining to each region, the blanket enrichment when present and the burnable absorbers specification.

The AP1000 PWR operates following the MSHIM™ core control strategy, an advanced operational strategy that entails operation with multiple control rod banks inserted in the core, including light tungsten banks and standard Ag-In-Cd banks[2][3]. The control banks configuration is shown in Figure 2. The banks used for MSHIM maneuvers are the M-banks, typically the light tungsten banks MA through MD, with the AO bank used for controlling the axial power distribution.

The AP1000 PWR advanced core design and operational features make application of an advanced core simulator like VERA-CS especially relevant for the analysis.

2 CODES EMPLOYED

VERA-CS includes coupled neutronics, thermal-hydraulics and fuel temperature components with an isotopic depletion and decay capability. The neutronics capability employed is based on MPACT [4], a three-dimensional (3-D) whole core transport code capable of generating sub-pin level power distributions. These capabilities are accomplished by obtaining the integral transport solutions to the heterogeneous reactor problem in which the detailed geometrical configuration of fuel components such as the pellet and cladding is modelled explicitly. The cross section data needed for the neutron transport calculation are obtained directly from a multigroup microscopic cross section library similar to those used in lattice physics codes. The 3D solution is obtained by means of a 2D-1D approach [5] which employs planar Methods of the Characteristics (MOC) solutions in the framework of the 3-D coarse mesh finite difference (CMFD) formulation. The axial coupling is resolved by one-dimensional (1-D) lower-order solutions (SPN in this case) and the planar and axial problems are coupled through the transverse leakage. The thermal-hydraulics and fuel temperature models are provided by the COBRA-TF subchannel code [6] being developed by CASL and Pennsylvania State University. The isotopic depletion is performed using the ORIGEN code system [7].

An extensive set of simulations has been performed with VERA-CS throughout this activity. The results presented are focused on Hot Zero Power (HZP) simulations, where given the fresh fuel and uniform temperature conditions it is possible to establish Monte-Carlo Continuous Energy (CE) reference solutions for validation of the VERA results.

The Monte-Carlo tools employed are KENO-VI and SHIFT. The KENO-VI [8] version used for this work is part of SCALE 6.2, and includes parallelization of the particle transport and improvements in the CE data and methods [9]. SHIFT is a general purpose radiation transport code that performs stochastic modeling of particle physics using the Monte Carlo method; it uses the Multiple-Set-Overlapping-Domain (MSOD) parallel scheme [11] that allows full domain replication, domain decomposition, and domain decomposition with overlap and multiple sets. Using MSOD, SHIFT has demonstrated linear strong scaling behavior out to 250,000 cores on the Oak Ridge Leadership Computing Facility (OLCF) TITAN machine. The libraries used have been generated by the AMPX code system [10] based on ENDF/B-VII.0 CE cross section library.

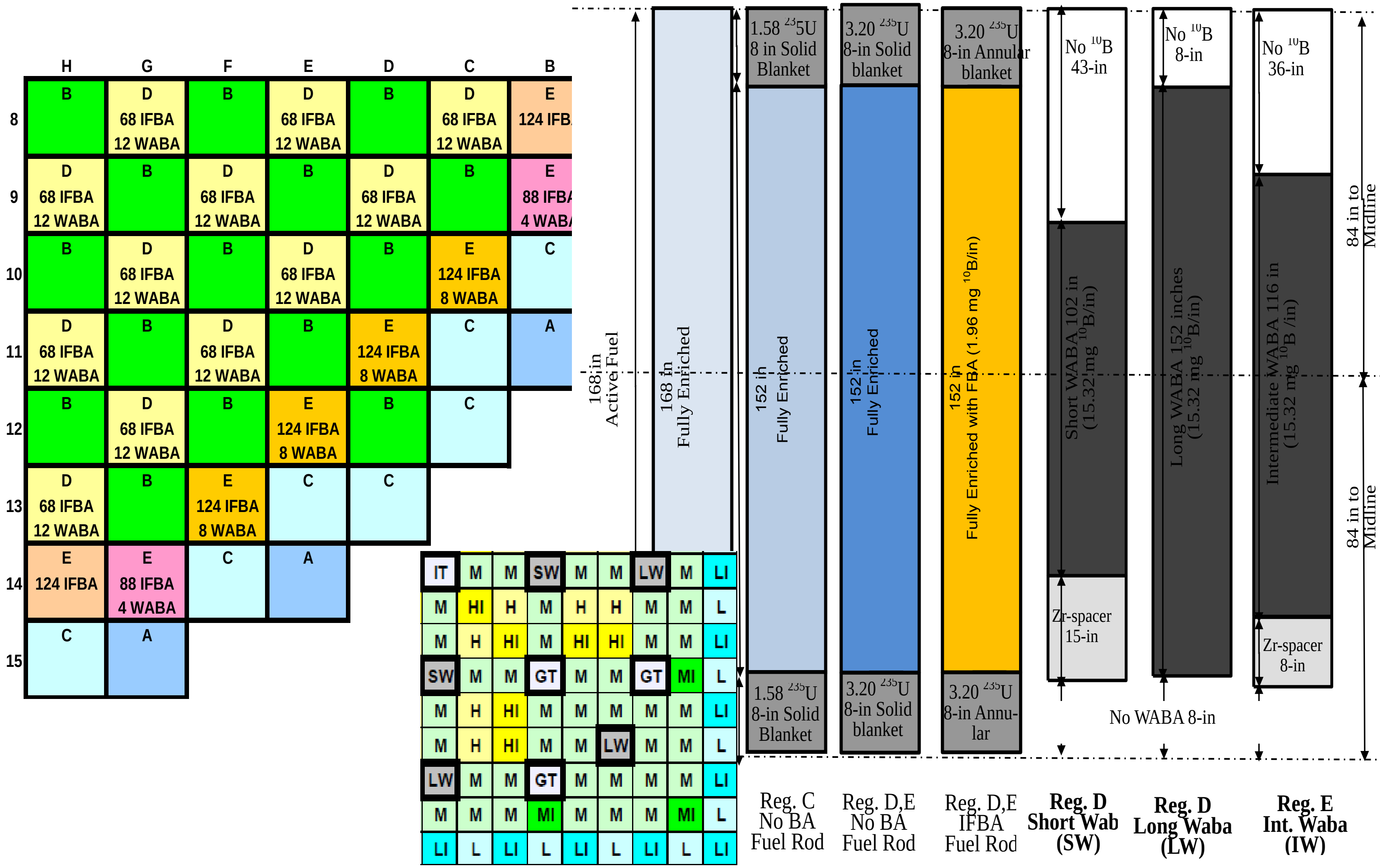

Figure 1 AP1000 PWR First Core – Fuel Loading Pattern (quarter core radial map) and Region D Fuel Assembly design (quarter assembly radial map)

Table 1 Fissile, IFBA and WABA Content for the AP1000 PWR First Core
("L": Long WABA, "S": Short-WABA, "I": Intermediate WABA)

Region Identifier	**Number of Assemblies**	**^{235}U Midplane**	**^{235}U Blanket**	**IFBA Rods**	**WABA Rods**
A	16	0.740	Absent	0	0
B	49	1.580	Absent	0	0
C	28	3.200	1.580	0	0
D	36	3.776	3.200	68	8L+4S
E(1)	8	4.376	3.200	88	4I
E(2)	4	4.376	3.200	124	0
E(3)	16	4.376	3.200	124	8I

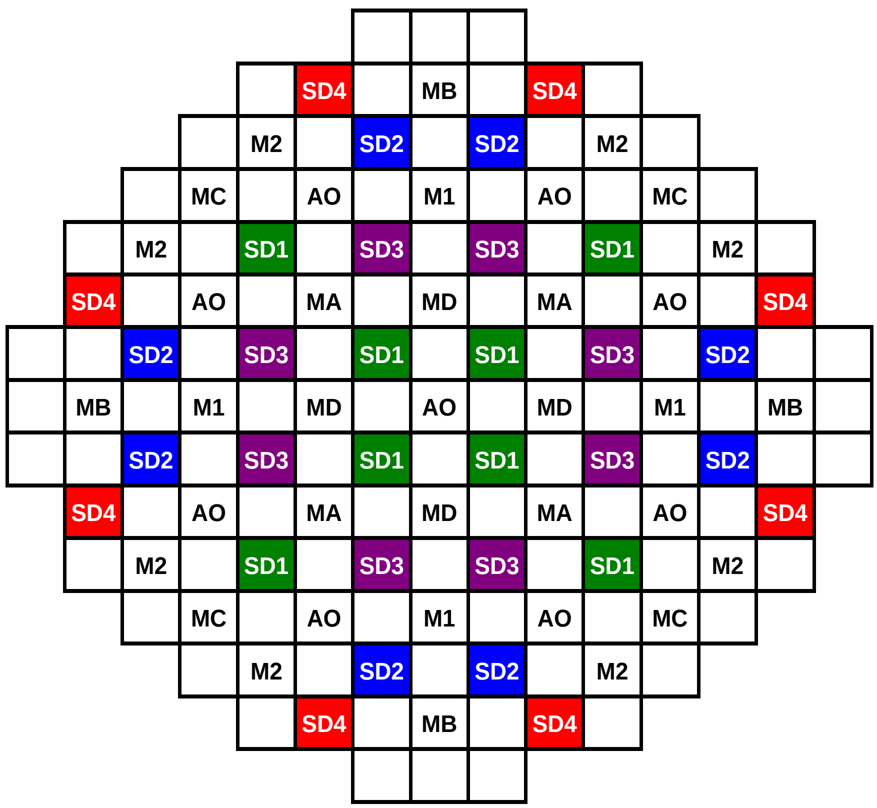

Figure 2 AP1000 PWR Control Banks Configuration

3 RESULTS

The simulations performed include 3D core All-Rods-Out (ARO) Critical Boron Concentration (CBC), reactivity coefficients and the Control Rod Worth, similarly to Nuclear Design calculations that support Zero Power Physics Tests (ZPPTs). In addition detailed fission rate spatial distribution comparisons have been performed on a range of geometries, including 2D core, 3D assembly and 3D core with multiple control rod banks inserted. Results using the VERA-CS INSILICO SP_N 3D solver were reported previously.[12]-[13] The VERA-CS results reported here are based on MPACT, which as previously discussed is the current VERA-CS neutronic capability.

3.1 Zero Power Physics Tests

Table 2 reports the HZP CBC at All-Rods-Out (ARO) conditions predicted by KENO, SHIFT and MPACT for the AP1000 PWR startup; the predictions from KENO and SHIFT are within 3 ppm (~30 pcm), while MPACT shows an underprediction of ~ -20 ppm. The boron worth from MPACT, -9.4 pcm/ppm, is in close agreement with KENO and SHIFT which both predict a boron worth of -9.6 pcm/ppm. KENO predicts an Isothermal Temperature Coefficient, ITC, of -2.7 pcm/F, vs. -1.9 pcm/F from MPACT (at the time of this paper SHIFT did not have perturbed temperature neutronic libraries to perform ITC calculations). The ITC calculation has been performed at a boron concentration of 1321 ppm, which is the HZP CBC prediction reported in Ref. [1].

Table 2 Zero Power Physics Tests Predictions

	KENO	SHIFT	MPACT
HZP Critical Boron (ppm)	1313	1316	1295
Boron Worth (pcm/ppm)	-9.6	-9.6	-9.4
ITC at 1321 ppm (pcm/F)	-2.7		-1.9

Table 3 reports the rod worth predictions, calculated for each control bank as the delta reactivity between HZP ARO conditions and the bank fully inserted, multiplied by 10^5 and reported as per cent mille (pcm). The rod worth predictions show excellent agreement for SHIFT and MPACT compared to KENO, with an average Root Mean Square (RMS) delta reactivity of less than 10 pcm and a maximum of 17 pcm over a total of 11 control banks.

The KENO calculations for this section rely on 25-100 billion particle histories for a quarter core geometry, with reported eigenvalue uncertainties equal to 0.1 ppm (HZP CBC), 2 pcm (Rod Worth), 0.1 pcm/ppm (Boron Worth), 0.05 pcm/F (ITC). The SHIFT calculations rely on 1 trillion particle histories and were performed in the framework of a 60 million core-hour allocation on the OLCF granted to a Westinghouse-ORNL team as part of an Early Science Award. These SHIFT calculations were executed over 240,000 computational cores on the OLCF TITAN with an execution time of ~2.5 hours per case.

Table 3 Rod Worth Predictions

		KENO	SHIFT		MPACT	
	Material	Worth (pcm)	ΔWorth (pcm)	ΔWorth (%)	ΔWorth (pcm)	ΔWorth (%)
MA	Tungsten	258	4	1.6%	1	0.5%
MB	Tungsten	217	-5	-2.3%	-6	-2.6%
MC	Tungsten	188	0	0.0%	1	0.4%
MD	Tungsten	234	5	2.1%	3	1.3%
M1	Ag-In-Cd	651	0	0.0%	-8	-1.2%
M2	Ag-In-Cd	887	4	0.5%	6	0.7%
AO	Ag-In-Cd	1635	17	1.0%	-11	-0.7%
S1	Ag-In-Cd	1079	14	1.3%	1	0.1%
S2	Ag-In-Cd	1096	-2	-0.2%	-11	-1.0%
S3	Ag-In-Cd	1124	16	1.4%	1	0.1%
S4	Ag-In-Cd	580	-4	-0.7%	-2	-0.4%
		RMS	9	1.3%	6	1.1%
		Max	17	2.3%	11	2.6%

3.2 Power Distribution

This section focuses on the comparison of power distribution, from normalized kappa fission, obtained from KENO, SHIFT and MPACT for various benchmark configurations. As a preliminary step, 2D lattice calculations have been performed showing virtually perfect agreement in power distribution from all codes (delta power RMS of 0.1% and maximum % delta power of 0.3% from MPACT vs. Monte-Carlo, KENO or SHIFT). Next, a 2D radial core slice with a 1.5-in stainless steel baffle radial reflector surrounded by water has been simulated, with power distribution results depicted in Figure 3 and summarized in Table 4. The KENO power distribution shown on the left plot of Figure 3 reflects, progressing from the center to the core periphery, the checkerboard loading pattern of Region 2 and 4, the power peaking on the ring of Region 5 fuel assemblies, the low power in Region 3 and especially Region 1 (natural U) outermost assemblies. There is excellent power distribution agreement between SHIFT and KENO, as shown in the central plot of Figure 3, with a pin ΔP RMS of 0.2% and max pin ΔP of 0.5%. MPACT is also in very good agreement with KENO: pin ΔP RMS of 0.7%, and max pin ΔP of 1.4 % located on the low power pins on the core periphery. The delta k-eff follows the trends discussed in the previous section, with excellent agreement for KENO and SHIFT and -170 pcm for MPACT vs. KENO. Both KENO and SHIFT rely on 25B particle histories for this calculation, with a less than 0.1% reported average power uncertainty.

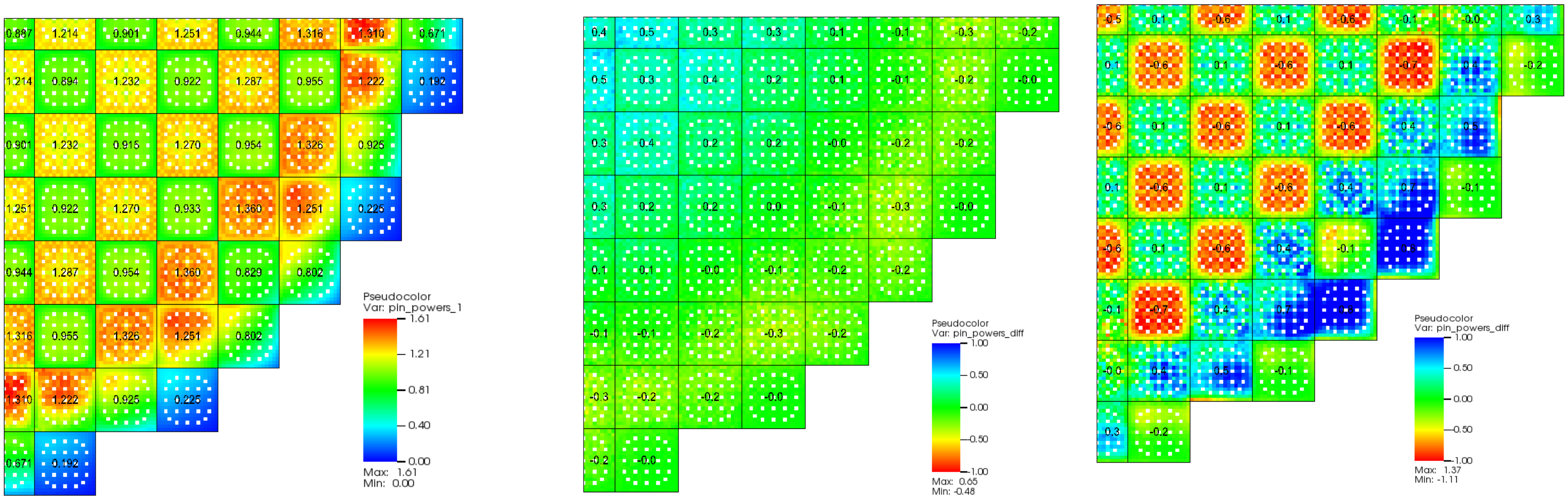

Figure 3 2D Radial Power Distribution (left), ΔP (SHIFT-KENO)x100 (middle), ΔP (MPACT-KENO)x100 (right)
Labels on the plots report Assembly Power (left), and Delta Assembly Power x100 (middle and right)

Table 4 2D Radial Core Results

Case	k-eff (SB ppm)	Δk-eff (pcm) SHIFT (MPACT)	RMS ΔP (%) SHIFT (MPACT)	Max ΔP (%) SHIFT (MPACT)
2D Core with Reflector	1.00114 (1315)	35 (-171)	0.2 (0.5)	0.7 (1.4)

Three-dimensional assembly simulations have also been performed, with reflective radial boundary conditions and simulating the entire fuel stack axially including explicit plena and plugs and homogenized nozzles and core plates. The resulting axial power distribution results for Region D fuel assembly is shown in Figure 4, with the KENO axial power profile plotted against the left “y” axis and the delta in relative power for either MPACT or SHIFT vs. KENO plotted against the right “y” axis. The impact on the power distribution of the axial heterogeneities, such as the spacer grids (8 Mixing Vane, taller, grids, and 4 Intermediate Flow Mixing, shorter, grids), and long and short WABA rods material transitions is evident. The short WABA poison region, with its offset with respect to the core midplane, causes a markedly top-skewed axial power profile at HZP conditions (at HFP the impact of the poison offset is counterbalanced by the thermal hydraulic feedback). Notwithstanding the resulting challenges on power distribution prediction, the agreement of MPACT with Monte-Carlo remains very satisfactory. This is confirmed in Table 5, which collects the results for all Regions fuel assemblies. The Monte-Carlo assembly simulations rely on 17.5 B particles, with a reported average power uncertainty of 0.05%.

The axial power distribution results for a 3x3 multi-assembly configuration of Region D and B fuel are plotted in Figure 5. A partially inserted control rod is present in the central assembly, and counterbalances the effect on the axial power distribution of the short WABA. A simulation for a quarter core configuration with multiple control banks inserted has also been performed, with axial power distribution shown in Figure 6. The summary results for both multi-assembly and quarter core configurations are given in Table 6, also displaying the banks degree of insertion. For practicality KENO results have not been generated for these cases. As shown in Figure 5 and Figure 6, the power distribution agreement for MPACT vs. SHIFT remains excellent for these very challenging simulations, with an RMS of ~0.5% and a maximum ΔP of ~2% over the entire problem geometry (an over 700,000 cells power comparison domain in the quarter core simulation). The SHIFT simulations rely on 75B (multi-assembly) and 500B (quarter core) particle histories employed, both reporting <0.1% average power statistical uncertainties.

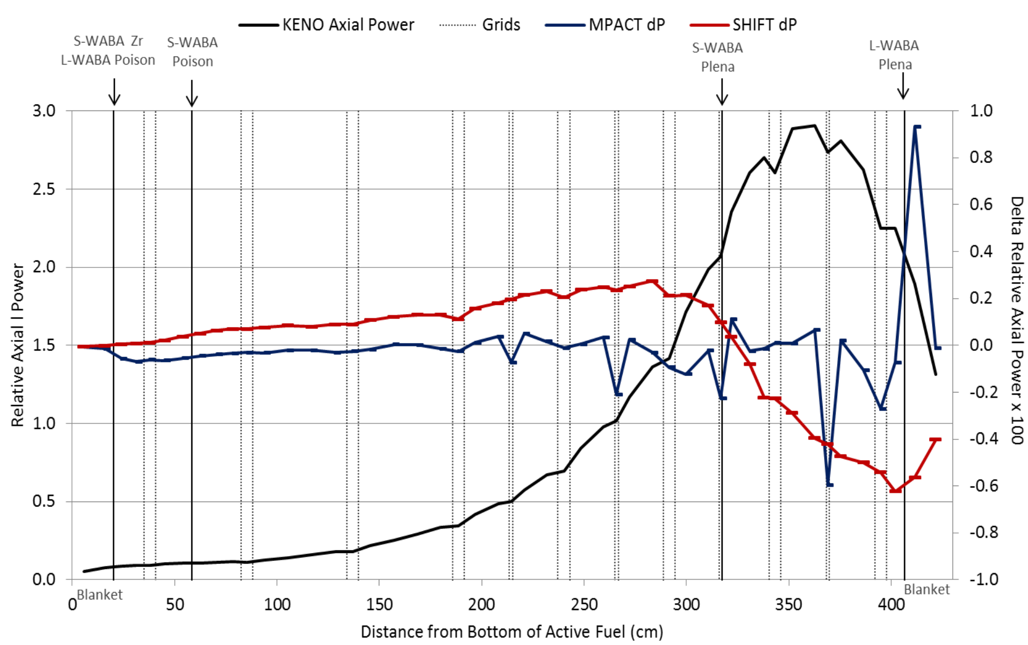

Figure 4 Region D Axial Power (Left “Y” axis) and Delta Axial Power (Right “Y” axis) - Reference is KENO, Delta Power SHIFT-KENO x100 and MPACT-KENO x100

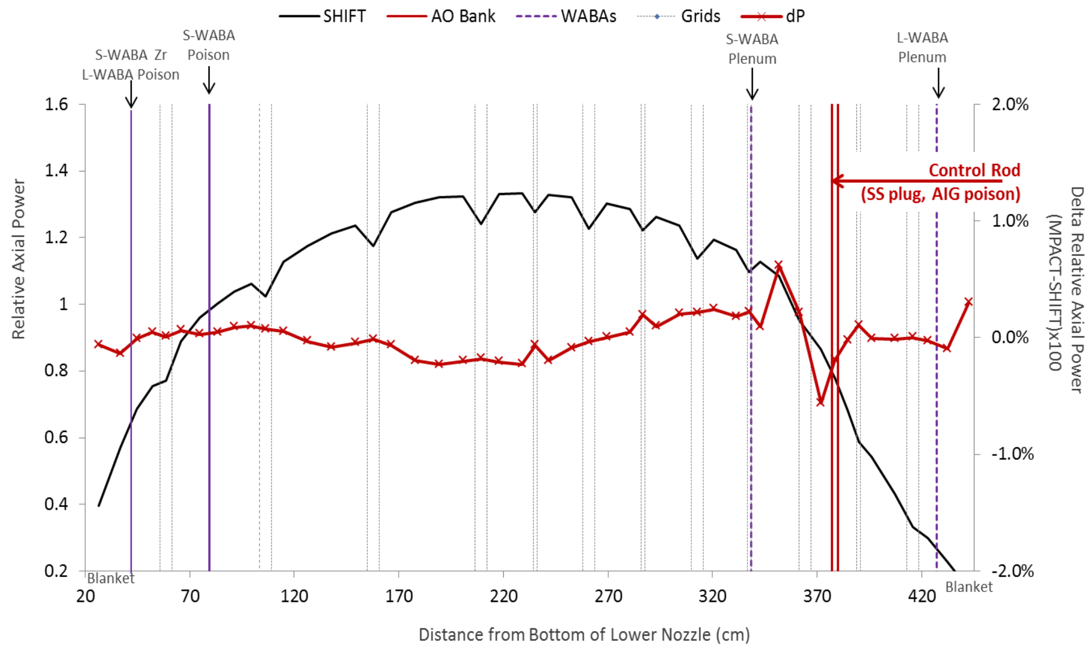

Figure 5 3x3 Axial Power (Left "Y" axis) and Delta Axial Power (Right "Y" axis) with Partial Bank Insertion - Reference is SHIFT, Delta Power MPACT-SHIFT x100

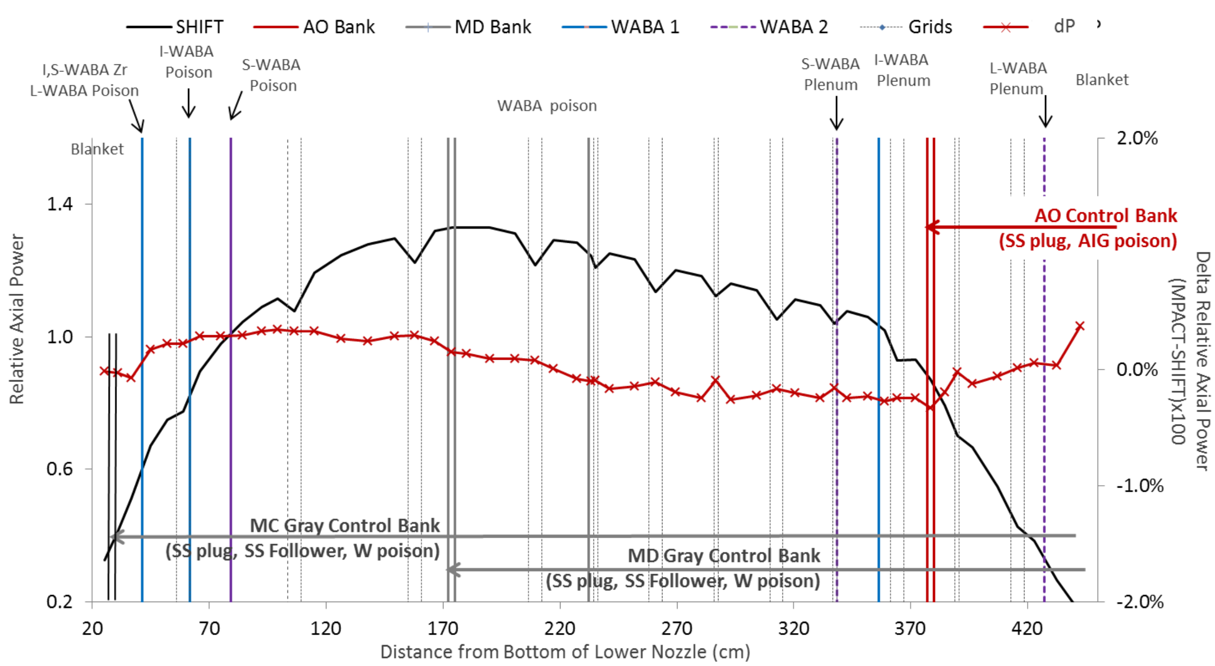

Figure 6 Core Axial Power (Left "Y" axis) and Delta Axial Power (Right "Y" axis) with Multiple Control Banks - Reference is SHIFT, Delta Power MPACT-SHIFT x100

Table 5 HZP 3D Assembly Results

Region Identifier	^{235}U Midplane (Blanket)	IFBA (WABA) Rods	k-eff (SB ppm)	AO (%)	Δk-eff (pcm) SHIFT (MPACT)	ΔAO (%) SHIFT (MPACT)	RMS ΔP (%) SHIFT (MPACT)	Max ΔP (%) SHIFT (MPACT)
A	0.740 (Absent)	No BA	0.9041 (No SB)	-2.9	33 (-185)	0.0 (-0.1)	0.1 (0.2)	0.4 (0.8)
B	1.580 (Absent)	No BA	1.0022 (947)	-0.9	40 (-140)	0.0 (0.1)	0.1 (0.2)	0.5 (0.7)
C	3.200 (1.580)	No BA	1.0027 (3268)	1.5	42 (-97)	0.0 (0.0)	0.1 (0.1)	0.3 (0.6)
D	3.776 (3.200)	68 (8L+4S)	1.0018 (1974)	80.9	41 (-117)	-0.1 (0.0)	0.3 (0.2)	1.2 (1.4)
E(1)	4.376 (3.200)	88 (4I)	1.0029 (3116)	53.4	37 (-123)	-0.3 (0.2)	0.4 (0.3)	1.4 (1.2)
E(2)	4.376 (3.200)	124 (0)	1.0032 (2773)	-0.5	40 (-164)	-0.1 (0.1)	0.1 (0.2)	0.5 (0.9)
E(3)	4.376 (3.200)	124 (8I)	1.0023 (2378)	93.6	34 (-225)	-0.1 (0.0)	0.3 (0.4)	1.4 (2.4)

Table 6 HZP 3x3 3D Assembly and 3D Quarter Core Results

Case	Bank Position (% Inserted)	k-eff (SB ppm)	AO (%)	Δk-eff (pcm) MPACT	ΔAO (%) MPACT	RMS ΔP (%) MPACT	Max ΔP (%) MPACT
3x3 Reg. B and D	AO, 17% In	1.00142 (1230)	-7.5	-120	-0.1	0.4	1.9
Quarter Core	AO, 17% In MD, 66% In MC, 100% In	0.98581 (1321)	-8.7	-118	+0.2	0.6	2.6

4 CONCLUSIONS

The results presented show excellent power distribution agreement from VERA-CS (MPACT) and Monte-Carlo (KENO and SHIFT) across a broad range of benchmark configurations pertaining to the AP1000 PWR advanced startup core. The delta power RMS for MPACT vs. SHIFT is 0.1% for 2D lattices, 0.5% for a 2D core radial slice, 0.2-0.4% for 3D assemblies (including cases with very top skewed power distribution), 0.5% and 0.6% for respectively multi-assembly and quarter core configurations with single or multiple control banks inserted. The maximum delta power discrepancy is in the 1-2% range for the most challenging simulations. It should be noted that rodded simulations are relevant for the AP1000 PWR since they are entailed as part of the MSHIM operational strategy. The excellent power distribution agreement from MPACT vs. Monte-Carlo at HZP conditions is encouraging for obtaining reliable HFP power distribution in the cycle depletion simulations to be performed next, for which it will not be possible to establish a reference Monte-Carlo prediction.

There is excellent agreement in the HZP ARO CBC predictions from KENO and SHIFT, which differ by only 3 ppm; MPACT predicts a roughly 20 ppm lower HZP CBC. The ITC prediction is in good agreement for KENO and MPACT, with a difference of 0.8 pcm/F. The rod worth is in excellent agreement for all codes and for all control banks. The results of these simulations reinforced the confidence in the startup predictions obtained by Westinghouse using its in-house core physics package.

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